Life Cycle Analysis of an Off-Grid Solar Charging Kiosk

Christopher J M Emmott[1,2,3], Abdalla A Jaoude[3,4], Antonio Urbina[1,5], Nicholas J Ekins-Daukes[1,2] and Jenny Nelson[1,2]

[1] Department of Physics, Imperial College London, London SW7 2AZ, UK
[2] Grantham Institute for Climate Change, Imperial College London, London SW7 2AZ, UK
[3] e.quinox, Imperial College Union, London SW7 2BB, UK
[4] Department of Mechanical Engineering, Imperial College London, London SW7 2AZ, UK
[5] Department of Electronics, Technical University of Cartagena, 30202 Cartagena, Spain
E-mail: christopher.emmott@imperial.ac.uk

***Abstract*–Solar power has a huge potential in electrifying rural communities, particularly in the developing world. It offers the possibility of a clean, affordable energy source which may reduce the environmental impact of existing, fossil fuel based sources. The life-cycle carbon emissions resulting from off-grid solar powered lighting solutions are an important factor influencing the environmental impact of implementing such solutions. This issue is particularly relevant when assessing the case for carbon financing for such a project. However, few studies have addressed the carbon saving potential of such off-grid systems. Here, we analyse a distribution model known as a Solar Charging Kiosk which enables access to photovoltaic electricity for rural, off-grid communities. Using a kiosk which has been established in the Bugesera region of Rwanda as a model system, the carbon savings avoided from reduced use of kerosene based lighting are calculated based on real system performance and usage data of customers of the kiosk. Strategies to further increase the emissions mitigation potential of the system are proposed.**

I. Introduction

1.3 billion people around the world have no access to modern forms of energy [1], and largely rely on inefficient and hazardous fossil fuels such as kerosene lamps for lighting. These forms of lighting must be replaced with modern solutions, most importantly for respiratory health and fire safety reasons but also for an improved light quality, decreased financial burden of relying on fluctuating kerosene prices and reduced environmental impact of energy supply.

Solar photovoltaics (PV) have proven to be an excellent modern energy source for off-grid communities in a number of applications, most prominently in domestic lighting (and other low power energy services such as mobile phone or radio charging) and PV powered pumps for agricultural irrigation [2]. They have been shown to provide a viable alternative to kerosene lighting, providing a cost effective, clean source of energy, helping to achieve a variety of development goals in health, education and economic development [3].

The low environmental burden of solar photovoltaics gives an added advantage to this solution since it can be financially accounted for through the clean development mechanism (CDM) [4] and voluntary carbon markets [5]. This can contribute towards the affordability of such products, enabling access to modern energy services for a greater proportion of communities [6], whilst also enabling other organisations to indirectly lower their own greenhouse gas (GHG) emissions and meet international targets. Indeed, the potential for GHG emission reductions is extremely great due to the large number of communities relying on GHG intensive energy. It has been estimated that if all fossil-fuel based lighting worldwide (including Kerosene, oil and gas lamps, as well as candles) could be replaced by cleaner alternatives; 244 million tonnes of CO_2 equivalent could be mitigated [3].

However, when considering potential emission reductions due to replacing an energy source, it is vital to consider the emissions associated with the alternative system of energy provision. This requires a detailed life cycle analysis to be conducted in order to calculate both the avoided emissions associated with implementing an alternative energy source, and the emissions associated with introducing this alternative.

A number of studies have looked at environmental impacts of solar lighting used in place of kerosene, using either solar home systems (SHS) or solar lanterns. However, the majority of these have neglected to include the emissions from the manufacture and distribution of the solar lighting product. Table 1 shows the carbon savings and emissions, from supplying a single household, with a solar lighting product in place of kerosene lighting, according to a selection of studies. These studies show large variations in system sizes and levels of usage, in particular usage levels differ substantially between studies of systems being used in the field and studies which assume a usage pattern. These results demonstrate the potential for carbon mitigation using solar lighting and show that emissions from manufacturing a solar lighting product are not negligible.

This study analyses the life cycle GHG emissions and avoided emissions associated with another solar photovoltaic based alternative, namely the Solar Charging Kiosk. This solution is based on a central PV system which acts as a centralised charging station for communities. Customers pay a deposit for a small battery box (a battery and associated electronics) which can be used for lighting, and other applications, in their home or workplace, and pay a small fee to recharge the battery box at the kiosk, thus creating a 'virtual grid'.

This distribution model was first developed in the west Bengali region of India in the early 1990s [7] and has since been trialled extensively in India and south east Asia, with well over 1.5 MW_p installed in Thailand, Vietnam and Laos PDR [8], [9]. However, to date there has been limited experience of this model in other regions [10], [11]. The model is represented diagrammatically in Fig. 1.

TABLE 1
ANNUAL AVOIDED EMISSIONS FROM SUPPLYING ONE HOUSEHOLD WITH SOLAR POWERED LIGHTING TO DISPLACE KEROSENE, AND THE EMISSIONS FROM MANUFACTURING AND PROVIDING THE SOLAR LIGHTING PRODUCT.

Source	Solar Lighting Product	GHG Emissions Avoided Annually ($kgCO_{2eq}$/year)	Total GHG Emissions ($kgCO_{2eq}$)
[12]	40-50 Wp SHS[a] with CFL[b]	76	Not considered
[13]	12-60 Wp SHS with CFL	79 - 448	Not considered
[14]	24-49 Wp SHS with CFL	510	312 - 833
[15]	10 Wp Solar Lantern (CFL)	115 - 236	108
[16]	15 Wp SHS with CFL	296	160
[16]	50 Wp SHS with CFL	477	650

[a] SHS: Solar Home System
[b] CFL: Compact Fluorescent Lamp

The Solar Charging Kiosk model is being advanced by e.quinox, a charitable organisation led by students of Imperial College London, which aims to create a blueprint design for such a kiosk that can be scaled and replicated. The organisation have already implemented four 'Energy Kiosks' in Rwanda and one in Tanzania, four of which are solar powered with one connected to the grid. These kiosks aim to be cost effective by charging the local population a small rental fee whenever they recharge their battery boxes. The income generated is used to finance the salary of the shopkeeper as well as any repairs or maintenance required. On a longer view, the returns would allow the kiosk to repay the initial capital investment, making it a profitable business.

II. SOLAR CHARGING KIOSK

A single solar charging kiosk, which was established by e.quinox in September 2010, is analysed in this study. The Kiosk is located at the village of Batima in the Bugesera district of Rwanda, which is situated close to the southern border with Burundi. This is a particularly favourable area for PV with an average annual insolation of 1920 kWh/m^2 [17].

A. System Description

The kiosk at Batima is designed to be able to support 130 battery boxes in constant use, and thus to supply 130 local households, although currently only 84 batteries are available at the kiosk. The PV system at the kiosk consists of two subsystems, which builds in redundancy in order to ensure reliability of the system. A photograph of the electronics for one of these subsystems is shown in Fig. 2. Each subsystem consists of: five 65Wp polycrystalline silicon PV modules, connected in parallel; a charge controller; a distribution box; a generation meter; fuses and circuit breakers; a 200Ah 12V deep-cycle lead-acid battery; and a 750W inverter. The AC output from this system is then used to charge the battery boxes via a multi-plug and standard AC charge controller. The kiosk also contains 3 CFL lights to aid its operation.

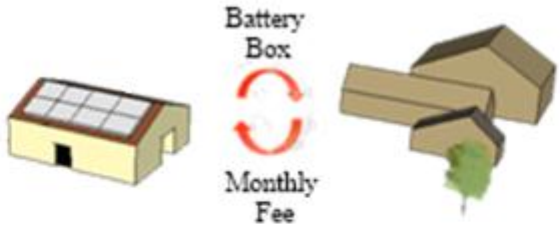

Fig. 1. Diagrammatic representation of the distribution model of the Solar Charging Kiosk concept.

The modules are mounted on top of a small building inside which the associated electronics are housed and the battery boxes can be charged. The mounting structure consists of steel bars which were sourced locally. A lightning and earthing rod were also installed to ensure protection of the system against lighting. All components in the kiosk are expected to last for 10 years except the inverters, batteries and CFL lights which have an estimated lifetime of 5 years.

The battery boxes supplied by e.quinox to the customers of the kiosk have a 5Ah capacity lead-acid battery; a single 12V output for use with the supplied 2W LED light; as well as a 240V AC output for use with other, non-lighting applications. A low charge power cut off is included to ensure longevity of the battery life by preventing over discharge, and a 70W inverter enables the box to supply an AC output. These battery boxes are expected to be replaced three times during the life of the kiosk (considerably shorter than the large, kiosk batteries), however, the LED light supplied with the battery boxes is assumed to last for the full lifetime of the kiosk.

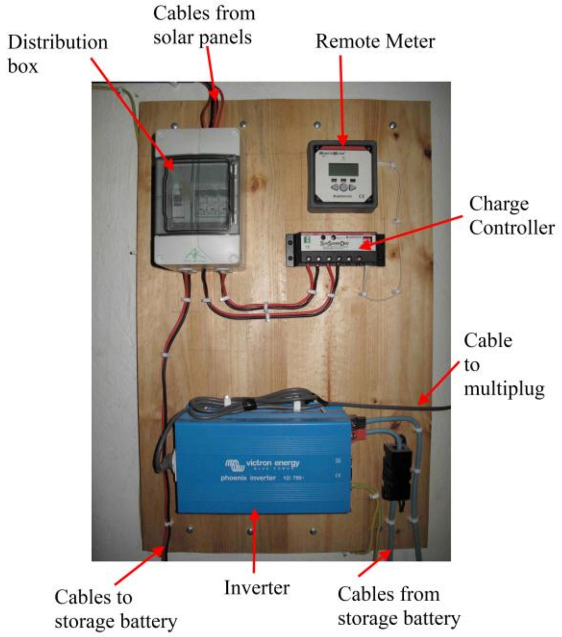

Fig. 2. A photograph of the electronics of one of the two subsystems in the kiosk.

B. *Usage Patterns*

The usage patterns of customers of the kiosk were investigated through analysis of the financial records held by the kiosk. These show the frequency with which each customer recharged their battery, and shows that the average period between recharges is approximately 16 days, but varies widely between customers. These records also show that 20% of the customers who paid a deposit for a battery box did not return to recharge the battery, and it is therefore assumed that these batteries are not in use.

In addition, a survey has been carried out of the kiosk customers in order to determine the use patterns and applications for which the battery boxes are used. From this survey, it was found that the battery boxes were used for lighting and, in some cases, for charging mobile phones (which was done via the AC output). In the cases where the battery box was used for phone charging, this was done once or twice a week, with the rest of the power being used for lighting.

III. LIFE CYCLE ANALYSIS

A. *Life Cycle Emissions*

A life cycle analysis was conducted of the solar charging kiosk described above to calculate the greenhouse gas emissions of the system. All GHG emissions assessed were converted into carbon dioxide equivalent considering a 100 year time horizon, according to [18]. The scope of the study encompasses all material inputs in constructing the kiosk including all transportation of imported materials to the site and emissions from manufacturing the components. A detailed material inventory for the kiosk, along with data from the literature as well as the ecoinvent database [19] was used to determine the GHG footprint of the kiosk. The following sections outline the major elements of the system.

1. *Photovoltaic modules*

The kiosk uses ten 65Wp polycrystalline silicon modules which are manufactured in China. The GHG emissions from manufacturing the modules was calculated based on data provided in [20] as well as analysing the life cycle inventory which this study was based on [21], and assuming all electricity usage to have an emissions factor of 900 gCO_{2eq}/kWh which is the average emissions factor for electricity in the Chinese grid [22]. This results in GHG emissions from manufacturing each module of 168 $kgCO_{2eq}$.

2. *Kiosk Balance of Systems*

The emissions from the balance of systems of the kiosk can be largely divided into two groups: basic materials such as copper wire and the mounting structure; and associated electronics.

The Mounting structure consists of 129 kg of steel rods, whilst the lighting and earthing rods consist of copper plated steel. The steel was assumed to be 27.3% from recycled material, which is the world average recycled content for steel [23], and emissions from manufacturing the steel were taken from the Inventory of Carbon and Energy from the University of Bath [24]. Emissions from the production of copper wiring and the plating of the lighting and earthing rods was taken from the ecoinvent database [19]. Emissions from the production of plastic tubing used in protecting the wires was taken from [24].

The major components in the associated electronics are the inverter, and the battery. Emissions from the production of the battery were based on the capacity of the battery, assuming 66 gCO_{2eq}/Wh which was calculated based on data in [25]. The emissions from the inverter were based on data provided for a 500 W inverter in the ecoinvent database [19] and scaled up to the size of the inverters used in the kiosk. The emissions from the charge controllers were based on [16], the multiplug on data in [19] and the CFL lights on [26].

3. *Battery Boxes*

The emissions from the manufacture of battery boxes themselves were assumed to be negligible and so only the emissions from manufacture of the component parts were considered. The lead acid battery and inverter were based on the same data as for similar components in the kiosk. The printed circuit board and other electronic components weigh approximately 50g and were assumed to have similar emissions by weight to a charge controller, emissions for which are given in [16]. The plastic casing weighs approximately 100g and the associated emissions were taken from [24]. Emissions from the LED light, which is supplied with the battery box, were based on [26] and the light holder on [16].

4. *Transport*

The mounting structure and lighting protection were locally sourced and thus transport for these materials was ignored. All the electrical components, with the exception of some wiring, were imported from China and the emissions from this transport were accounted for. The combined weight of all these components, including the battery boxes, kiosk inverters and batteries, the PV modules, and including all the expected replacement components, is 696 kg. These were assumed to be transported by ship for 11,727 km and by road for 1200 km (from the coast in Tanzania to Rwanda). The emissions for these two modes of transport were 7.41 gCO_{2eq}/tonne*km and 165 gCO_{2eq}/tonne*km, respectively [16].

B. *Avoided Emissions*

The principal source of lighting for the community in which the solar kiosk is situated, as well as for much of the developing world, is kerosene lanterns, and this is the main source of GHG emissions displaced by the use of the solar charging kiosk. Additionally, battery boxes are used to charge mobile phones, this replaces the need to take phones to the nearest electrified town to be charged from grid supplied electricity. The power generated by the kiosk PV system is also used to power lighting within the kiosk. However, since this lighting application would not exist without the kiosk, no avoided emissions were accounted for due to power use within the kiosk itself.

In order to calculate the GHG emission reductions from the use of the battery boxes, the frequency of recharges for each customer was taken from the records held by the kiosk. This provided a value for the total amount of energy from the kiosk PV system which is utilised by the kiosk customers. A proportion of this energy was used to charge mobile phones with rest being assumed to provide lighting, and thus displacing kerosene. The amount of GHG emissions associated with each of these activities in the baseline is shown in table 2.

The total number of hours for which all the battery boxes were used to charge phones was calculated assuming that all battery boxes which are in use (80% of the total number of boxes) charge one phone for one hour per week. The energy remaining in the battery boxes was assumed to be used only for lighting, and was calculated according to (1), where N_{re} is the number of battery recharges at the kiosk in a given time period; C_{batt} is the capacity (in Wh) of an individual battery box; L_{batt} is the percentage to which the battery can discharge (set at 20% by the over-discharge protection circuit); P_{ph} is the power used for mobile phone charging (in W); T_{ph} is the total time used for phone charging in the given time period (in hrs); η_{AC} is the efficiency with which AC power is outputted by the battery box (assumed to be 70%); η_{DC} is the efficiency with which DC power is outputted by the battery box (assumed to be 80%); and P_{light} is the power consumption of one LED light (in W).

$$\text{Hours of lighting} = ([N_{re} * C_{batt} * (1 - L_{batt})] - [P_{ph} * T_{ph} / \eta_{AC}]) / (P_{light} / \eta_{DC}) \quad (1)$$

Degradation of the batteries in the battery box was accounted for in the assumption used for the efficiency of the AC and DC outputs of the battery box. These were estimated to be 70% and 80% respectively, which is lower than would be expected, in order to take into account degradation of the battery.

TABLE 2
GHG EMISSIONS PER HOUR FOR ACTIVITIES IN THE BASELINE SCENARIO

Activity	Assumptions	GHG emissions (gCO_{2eq}/hr)
Kerosene Lighting	Emissions factor of Kerosene: 2473gCO_{2eq}/L [14] Fuel use of kerosene lantern: 0.05L/hr [14]	123.6
Mobile Phone charging	Emissions factor of grid supply: 900gCO_{2eq}/kWh [22] Power consumption of phone charger: 5W	4.5

IV. RESULTS

This analysis uses real data from an existing solar charging kiosk in the Bugesera district of Rwanda. The emissions from establishing and operating the kiosk over its 10 year lifetime are shown for the various components of the system in Fig. 3. The total project emissions from establishing the kiosk facility are 5,904 $kgCO_{2eq}$, approximately half of which is due to the battery boxes supplied to customers of the kiosk. The avoided emissions from the use of battery boxes from the solar charging kiosk were calculated, using the above

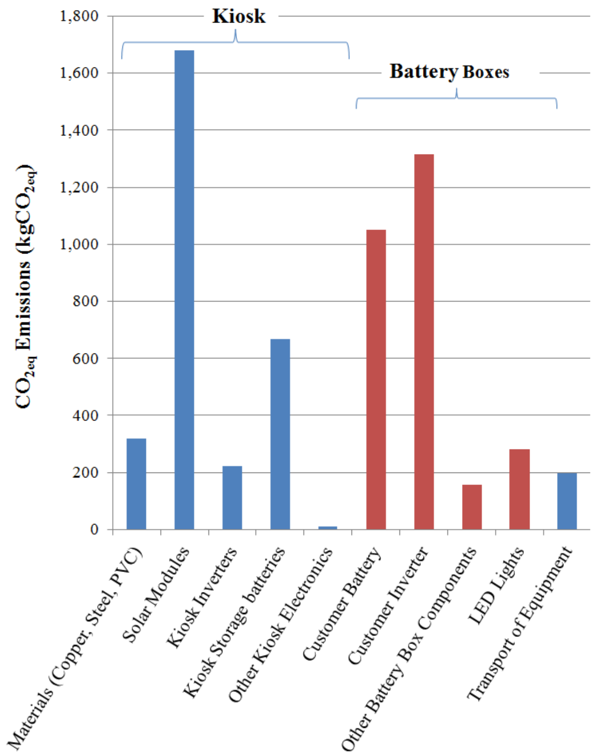

Fig. 3. Project emissions from various components associated with establishing a Solar Charging Kiosk and maintaining it for ten years.

methodology, for a period of one year. The amount of energy provided to the customers from the PV system, through the individual battery boxes, was calculated from the financial records held by the kiosk and found to be 94.3 kWh annually. This results in an annual GHG emissions saving, from displaced kerosene usage and grid phone charging, of 3,467 $kgCO_{2eq}$/year.

Fig. 4 shows the GHG emissions from establishing the kiosk in comparison with the avoided emissions in a single year. This shows that the GHG payback time for the kiosk is equal to 1.7 years, which is well below the expected lifetime of the system of 10 years. By considering the avoided GHG emissions over the total expected lifetime of the kiosk, the emissions associated with establishing the kiosk are 17% of the avoided emissions.

A functional unit of "provision of a single light to one household" (equating to a single battery box) was considered and the results are summarised in table 3. These results can be approximately compared with the results in the literature for SHS and solar lanterns, as shown in table 1. However, since values provided in the literature describe a range of service provision, these figures are not directly comparable. As a guide, a SHS or solar lantern using a CFL light source and with a PV capacity of approximately 10 Wp would be able to supply a similar service to a single battery box and LED from the solar charging kiosk (i.e. a single light source and phone charging) [14].

The avoided emissions resulting from providing the solar charging kiosk service to one household is considerably lower than results for SHS shown in the literature (see table

1). This suggests that the battery box is not fully providing the customers lighting requirements, possibly due to design of the LED light or due to the cost or inconvenience of recharging the battery at the kiosk.

TABLE 3
ANNUAL AVOIDED EMISSIONS FROM SUPPLYING ONE HOUSEHOLD WITH THE SERVICES OF A SOLAR CHARGING KIOSK, AND THE TOTAL EMISSIONS FROM SUPPLYING THIS SERVICE FOR 10 YEARS.

System	GHG Emissions Avoided Annually ($kgCO_{2eq}$/year)	Total GHG Emissions ($kgCO_{2eq}$)
Current Solar Charging kiosk	52.53	89.5
Optimised Solar Charging Kiosk	52.53	45.5

A. Optimising the kiosk

In order to assess how well the kiosk is optimised, a simulation of the output of the system was completed using the PVsyst software package [27]. This showed that expected output from the PV system is approximately 787 kWh, taking into account system losses from; module temperature, soiling, the angle of the modules and conversion losses, which were estimated by PVsyst to be 36%. The estimated power production is substantially higher than the power used through the customer battery boxes (which was calculated to be 94.3 kWh). This can be partially accounted for due to the energy consumption of the operation of the kiosk itself as well as losses in the system which were not accounted for in the PVsyst model. However, the principle reason for the poor utilisation of the PV system output is due to over-sizing of the kiosk. Two factors result in over-sizing of the kiosk. Firstly, the number of battery boxes that the kiosk was designed for are not available at the kiosk. Secondly, and most importantly, the kiosk is over-sized in order to ensure an efficient service can be supplied to customers, such that it is possible to service a surge of customers coming to the kiosk in one day.

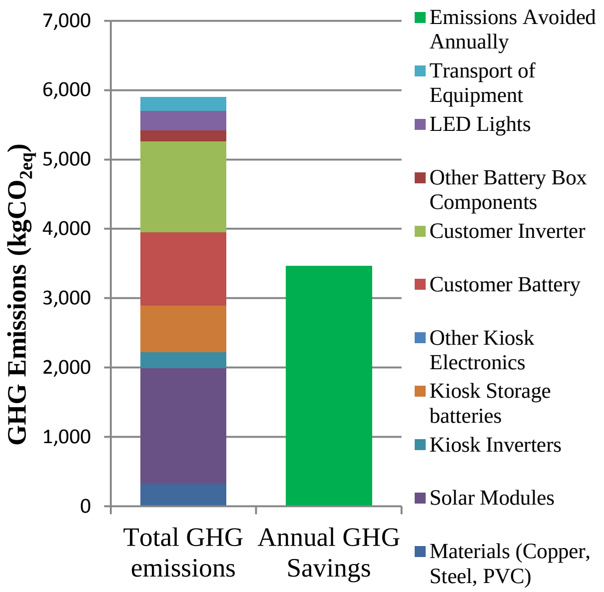

Fig. 4. GHG emissions from establishing the kiosk and maintaining its operation for 10 years (left), as compared with emissions mitigated *annually* from the use of the kiosk service (right).

If more battery boxes were made available at the kiosk (and the demand existed for these) then more of the power produced by the PV system could be utilised and subsequently the amount of GHG emissions mitigated by the kiosk would be increased. This would be possible if management of the battery charging could be better controlled, either though controlling timing of when customers come to the kiosk, or through customers swapping batteries from a surplus kept at the kiosk.

In addition, our calculations also show that a battery box supplies an average of 35 hours of lighting to a household. This equates to the avoided use of approximately 1.8 litres of kerosene per month which is considerably lower than published estimates of kerosene consumption in low income, rural communities worldwide, which range from 3 to 30 litres per month per household [28]. This adds to the evidence that the battery boxes are not being used to supply all the lighting needs of the customers and, therefore, presents an opportunity for improvement of this distribution model. This limited utilisation of the battery boxes for lighting may be partially due to the fact that battery boxes are only supplied with a single LED light.

If the amount of power used by the customers (via the use of the battery boxes) could be increased, from the currently observed level of 12% of predicted power produced by the PV system, to a figure of 50%, then the avoided GHG emissions from the same system would be greatly increased. This optimised level of usage of the predicted power produced by PV system allows for: power consumption for running the kiosk; losses not accounted for in the PVsyst model; a limited period of system autonomy; and a degree of flexibility in being able to serve a surge of customers in one day. The comparison of the carbon emissions from establishing the kiosk, with the avoided emissions resulting from this optimised case, is shown in Fig. 5. It has been assumed that each individual battery box maintains the same usage pattern (thus still not supplying all lighting needs) but the number of customers of the kiosk is increased.

In order to enable 50% of power produced by the PV system (as calculated in the PVsyst model) to be used by the customers, an extra 192 battery boxes would be needed at the kiosk (not including replacements), in addition to the 18 original battery boxes which are not currently being used. The GHG emissions avoided annually from this optimised system were found to be 14,449 $kgCO_{2eq}$, whilst the additional GHG emissions from manufacturing and transporting the additional batteries and their replacements over 10 years is equal to 6,664 $kgCO_{2eq}$ (see Fig. 5). This results in a GHG payback time of 0.87 years, a significant reduction compared to the previously calculated 1.7 years.

The GHG emissions and savings from supplying the optimised solar charging service using a functional unit of one household (i.e. one battery box) are shown in table 3. This shows a considerable improvement on the existing

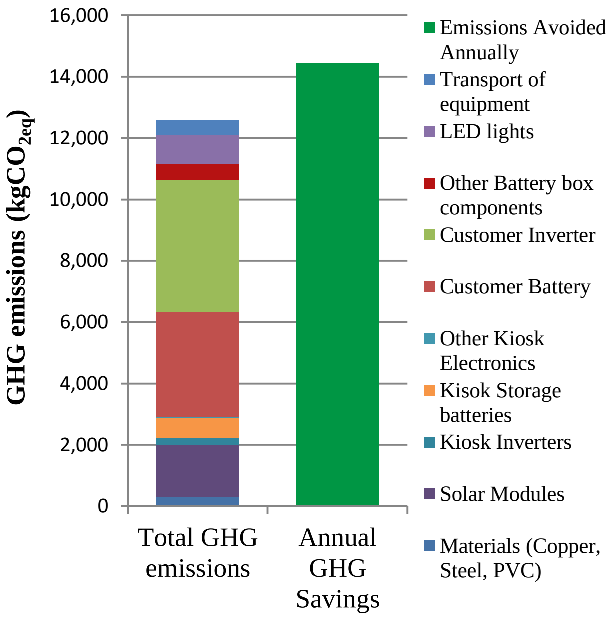

Fig. 5. GHG emissions from establishing the optimized kiosk and maintaining its operation for 10 years (left), as compared with emissions mitigated *annually* from the use of the optimised kiosk service (right).

situation of the kiosk and shows the potential to provide much greater GHG emissions mitigation than is currently observed.

CONCLUSION

This study analysed the GHG emissions resulting from establishing a solar charging kiosk in rural Rwanda as well as the emissions that are avoided due to reduced kerosene usage. The emissions from supplying the services of the kiosk to a single household are of a similar level to an equivalent service supplied by a small SHS or solar lantern, as shown in the literature. The kiosk analysed is likely to save approximately 29 tonnes of CO_{2eq} over its 10 year lifetime, by supplying services to 66 households. If the system was optimised to better make use to the power produced by the PV system, 245 households could be serviced, mitigating 132 tonnes of CO_{2eq} over the kiosk's 10 year lifetime.

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